Triboelectric sensor as a dual system for impact monitoring and health assessment of composite structures.

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Abstract. Bird strikes, hailstone impacts, and other type of mechanical collisions are quite frequent for a number of crucial and important structures, including aircrafts, wind turbines, bridges and other composites structures. These impacts harm the integrity of the composite laminates used in their structures which results in delamination and other failures which reduces their overall lifetime. Hence, the prediction of the damage caused by these impacts can be used to assess assessing the integrity of the composite structures.

This paper suggests a triboelectric sensor based on polyvinyl fluoride nanofibers and investigates its potential as a dual system for impact monitoring and health assessment of composite structures.

For the purpose an experiment is designed where composite plates are subjected to controlled velocity impacts using a drop-weight impact machine. During the experiment, the fabricated triboelectric sensor is adhered to the composite specimens with the aim to measure the magnitude of the impacts and predict the severity of the damage caused in the composite structures. The results demonstrate that the developed triboelectric sensor can be successfully used for measuring the magnitude of the impacts. Our

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results show that the sensor electric response increases with the increase of the impact velocity. Additionally, the produced voltage and current outputs show a linear directly proportional relationship to the measured impact velocity, which facilitates greatly the estimation of the impact velocity from the measured electric response.

Furthermore, the paper also proves that the electrical responses of the suggested sensor can also be used to predict the severity of the damage caused by the controlled velocity impacts in composite structures.

The findings of this research extend the application of triboelectric sensors for the dual purposes of impact monitoring and health assessment. In other words, the results demonstrate a new approach to predict the health state of composite structures using the electric responses of the triboelectric sensor. These results are of a great interest for the industry as the delamination caused by impacts is very difficult to detect by visual inspections.

Keywords: Structural health monitoring; Triboelectric sensor; Self-powered; Velocity sensor; Composite Structures; Nanofibers.

1 Introduction

Impacts are frequent in airplanes, wind turbines, bridges and other civil composite structures. For example, the operational state of wind turbines can be seriously affected due to the impact of hailstones. The integrity of aircraft composite structures can be seriously damaged because of the collisions with birds. Therefore, impacts are responsible for a big part of accidents in aerospace and civil structures affecting the working and health state of aircrafts, bridges and other structures made of composite laminates. Consequently, the detection and quantification of impacts is of critical importance for the health assessment of composite structures.

It is well known that impact sensors are very important for the detection and the correct quantification of impacts. Impact sensors are usually classified according to their working mechanism as piezoelectric [1, 2], resistive [3], triboelectric [4, 5], capacitive [6], and optical types [7]. Among them, the sensors operating based on the triboelectric effect are attracting considerable attention among the research community. The main advantage of triboelectric sensors is that they are self-powered and do not require an external power supply or battery. Furthermore, the materials used in triboelectric sensors as for example teflon, PVC or aluminium are cheap and commonly available in our daily life, which results in important cost-savings.

In the last years, several papers have investigated the applications of triboelectric nanogenerators as energy harvesters [39-41] and self-powered active sensors for pressures [8-11], touches [12, 13], vibrations [14, 15], accelerations [16-18], dynamic motions [19, 20], and velocities [21-23]. For example, in ref. [21], the potential of a triboelectric sensor for measurement of rotatory velocities in the range between 100 and 500 rpm is investigated. The results showed that the voltage sensor responses increase from 17 V to 31 V as the rotational velocity changes from 100 to 500 rpm. Other studies as refs. [22, 23] suggest that triboelectric sensors can be successfully used as self-powered wind speed sensors. However, there are no previous studies to report about the potential of triboelectric sensors for the prediction of the damage caused by impacts in composite structures.

It is well known that materials utilized in the fabrication of triboelectric sensors are normally selected from positive and negative sides of the triboelectric series. However, in the design of the current triboelectric sensor a combination of two cost-effective polymers namely polyvinylidene fluoride (PVDF) and polypropylene (PP) is used, and both materials are chosen from the negative side of the triboelectric series. The selection of the materials is attributed to their differences in charge affinity as the electron affinity of PP is lower as compared to PVDF. Additionally, our choice is motivated be the need to investigate the performance of triboelectric sensors when the coupling materials are selected from same negative side of the triboelectric series. This is because a significant number of materials on the positive side of the triboelectric series are natural biological materials (e.g. fur, wool or cotton) that are difficult to use in practical devices [42].

In the design of the sensor, polyvinyl fluoride nanofibers are selected as negative triboelectric material because of their strong electron attracting ability [24-26]. This is attributed to the large amount of fluorine in PVDF and the large surface area of the nanofibers, which results in a strong tendency to steal electrons from other triboelectric mats

[9]. In contrast, a film of polypropylene is used as positive triboelectric mat due to its low-cost and lower electron affinity as compared to PVDF.

The first aim of this paper is to demonstrate the potential of the developed triboelectric sensor for monitoring impacts in composite structures like e.g. aircrafts. For this study, composite plates equipped with a triboelectric sensor are subjected to various impacts using a drop-weight impact machine with velocities ranging from 4.6 to 11.6 km/h. Then, the sensor electric responses are measured in the form of voltage and current using a commercial oscilloscope and digital multimeter respectively. The idea is to investigate if the amplitude of the voltage and current signals is affected by the velocity of the impacts. The results show that the sensor electric outputs increase with the increase of the impact velocities applied to the composite plates. According to our results, a strong linear relation between the velocity of the impacts and the sensor electric outputs was observed. Additionally, the voltage and current outputs show very high impact sensitivity for the range of velocities between 4.6 and 11.6 km/h.

The second part of the manuscript investigates the potential of the fabricated sensor for the estimation of the health state in composite structures. In this regard, we propose a new approach to predict the damage state of the composite specimens using the correlation between the voltage output generated by the impact and the delamination size of the composite plates. Based on this simple bidimensional relationship, the health state and the delamination size of the composite specimens is predicted.

The main contributions of this study can be summarised as follows: First, this work demonstrates the applications of triboelectric sensors for monitoring impacts in composite structures through measuring the velocity of the impacts. This is very important as impacts can harm the integrity of the composite structures through delamination and other fault mechanisms. Secondly, this paper proposes a new method for the prediction of the delamination caused by impacts, which can be potentially used for assessing the severity of damage caused by impacts in aeronautical and civil composite structures. In summary, the findings of this work can be potentially used to demonstrate the dual potential of triboelectric sensors for impact monitoring and prediction of the damage in composite structures, such as aircrafts or wind turbines.

The rest of the paper is organised as follows: Section 2 describes the design and fabrication process of the triboelectric sensor. Section 3 shows a brief overview of the working mechanism of the triboelectric sensor. Section 4 explains the methodologies used to study the potential applications of the sensor for impact and health assessment in composite structures. Section 5 presents, analyses and discusses the experimental results obtained during the experiments. The last section offers some conclusions.

2 Preparation of the triboelectric sensor

The triboelectric sensor used for this study was fabricated using polyvinylidene fluoride nanofibers and a film of polypropylene. The aim of this section is to explain the structural design and fabrication process of the triboelectric sensor.

2.1 Design of the sensor

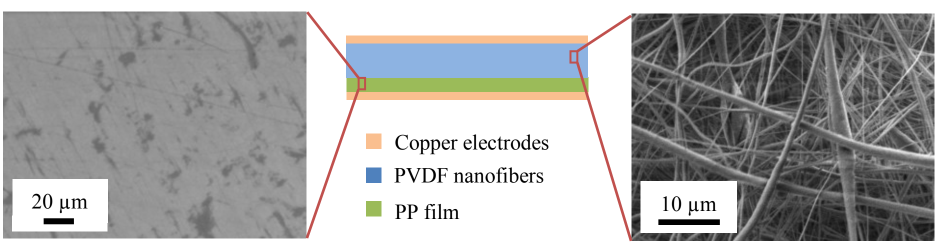


Fig. 1. Schematic description of the sensor structure: The left inset of the figure shows a SEM image of the polypropylene film, while the right inset shows a SEM image of the polyvinyl fluoride nanofibers.

The structure of the triboelectric sensor is schematically illustrated in Fig. 1 and can be divided into two sections: The top plate of the sensor consists of polyvinylidene fluoride nanofibers deposited on copper foil and the bottom plate of the sensor is based on a polypropylene film adhered to copper foil. The role of the copper foils is to act as electrodes for the sensor while the PVDF and PP serve as triboelectric frictional mats. In the design of the sensor, polyvinylidene fluoride nanofibers are purposely chosen according to the triboelectric series because they can easily gain electrons from the polypropylene film as detailed in supplementary figure S1. This behaviour can be explained by the large composition percentage of fluorine in PVDF and the large effective contact area of the nanofibers, which results in a strong ability to gain electrons (negative charges) from other triboelectric mats [9].

A scanning electron microscope (SEM) image of the polypropylene film is depicted at left-hand side of Fig. 1. The image shows a few scratches uniformly distributed on the surface of polypropylene, which are beneficial to increase the contact surface of the frictional layer. Another more detailed SEM image of the PVDF nanofibers is shown at the right-hand side of Fig. 1. From the image, a dense array of PVDF nanofibers with random orientations can be appreciated. The average diameter of the nanofibers was measured to be about 800 ± 350 nm. Furthermore, it can be observed that the nanofibers contain a few beads which can be attributed to the nature of the polymer solution used in the electrospinning.

2.2 Fabrication of the sensor

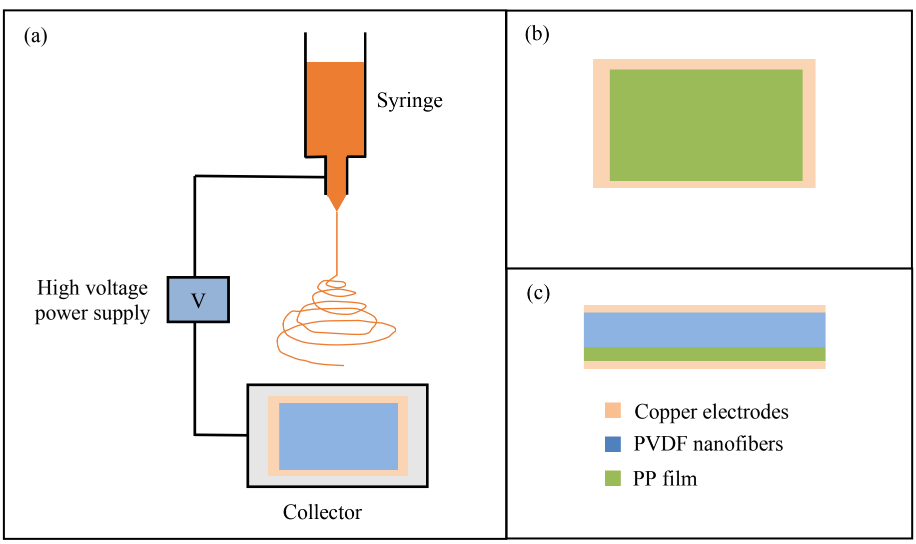


Fig. 2. Schematic diagram of the sensor fabrication process: (a) Preparation of the sensor top plate. (b) Preparation of the sensor bottom plate and (c) final assembly of the triboelectric sensor.

The fabrication process of the triboelectric sensor is depicted in Fig. 2. First, a membrane of interconnected PVDF nanofibers (2 mm) is electrospun on copper foil to form the top plate of the sensor as shown in Fig. 2a. To prepare the solution for electrospinning, 2 g PVDF pellets are dissolved into 10 ml solvent mixture of N,N-dimethylformamide and acetone (4/6). Then, the chemical solution is electrospun by a Nanon-01A electrospinning unit using the following operational conditions: voltage applied 15 kV, spinning distance 15 cm, feed rate of 1 ml/h, 21-gauge needle and static collector. It is important to mention that the nanofibers are deposited on a copper foil which acts as collector for them during the electrospinning. Secondly, a thin polypropylene film (25 μm) is adhered to copper foil by a double-sided adhesive copper tape to form the bottom plate of the sensor as detailed in Fig. 2b. Finally, the top and bottom plate are assembled to produce the triboelectric sensor (fig. 2c). The sensor is sealed with polyethylene terephthalate film which acts as a protection layer. The dimensions and the weight of the fabricated triboelectric sensor are 55 x 55 mm and 6.75 g, respectively.

In summary, the fabrication process of the sensor is very simple and does not require expensive materials or technologies, which makes the process cheap and easy to perform [27, 28]. Moreover, the process can be easily upgraded for large-scale production, which suggests a promising method for fabrication of such sensors on an industrial scale using a low-cost technology.

3 Working mechanism of the triboelectric sensor

The working principle of the triboelectric sensor is schematically depicted in Fig. 3. The mechanism is based on the combination of contact electrification and electrostatic induction [29, 30]. In the initial state, there is no friction between the polypropylene and the polyvinyl fluoride nanofibers. As a result, there is no contact and separation of the triboelectric charges which results in no electric output as shown in Fig. 3(a). When the composites are impacted, the triboelectric sensor is deformed as result of the impact. Therefore, PVDF and PP rub against each other which induces negative charges on the surface of the PVDF and positive charges on the surface of the PP. As a result, the positive and negative charges are separated which result in a potential difference between the two electrodes as detailed in Figs. 3 (b-d). Therefore, the sensor electric responses are generated by the contact and separation of two triboelectric layers with opposite polarity. After the impact, the generated triboelectric charges disappear, and the sensor returns to its original state.

This is a self-powered mechanism and thus the triboelectric sensor does not require an external power supply, which is completely different from other conventional sensors [31]. It is worthy to note that although the operating principle of the sensor is self-powered, the oscilloscope and multimeter used to measure the sensor electric signals requires an external power supply or battery.

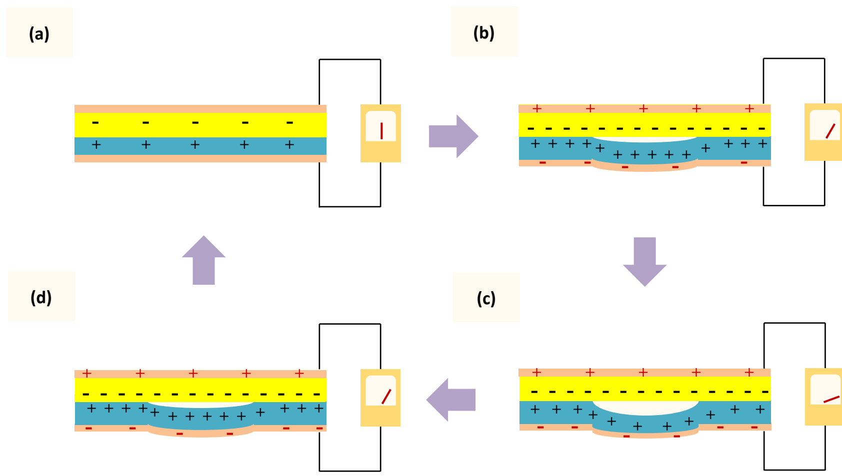


Fig. 3. Work[...] the triboelectric sensor: (a) Before im[...] [...]arious separation st[...] [...]ctric sensor during the impact. The p[...] [...] are not illustrated in the figure for the purpose of simplification.

4 Description of the experiment

4.1 Demonstration of the sensor as an impact sensor

The main objective of the experiments is to verify that the sensor electric responses are affected by the velocity of the impacts. This is important as we are aiming to expand the applications of triboelectric sensors for measurement of impact velocities in composite structures, such as airplanes, wind turbines and bridges.

A schematic diagram of the experimental setup is shown in Fig. 4a. Initially, the composite plates are impacted with controlled impact velocities using a drop-weight impact machine (Instron CEAST 9350). It is important to mention that the velocity of the impacts is varied in the range between 4.6 and 11.6 km/h with small increments of ~ 0.7 km/h. Subsequently, the sensor electric responses in form of voltage and current are measured using a commercial oscilloscope (Tektronix 2012 B) and a digital multimeter (Agilent 34410A). The purpose of the experiment is to verify that the sensor electric responses are dependent on the velocity of the impact.

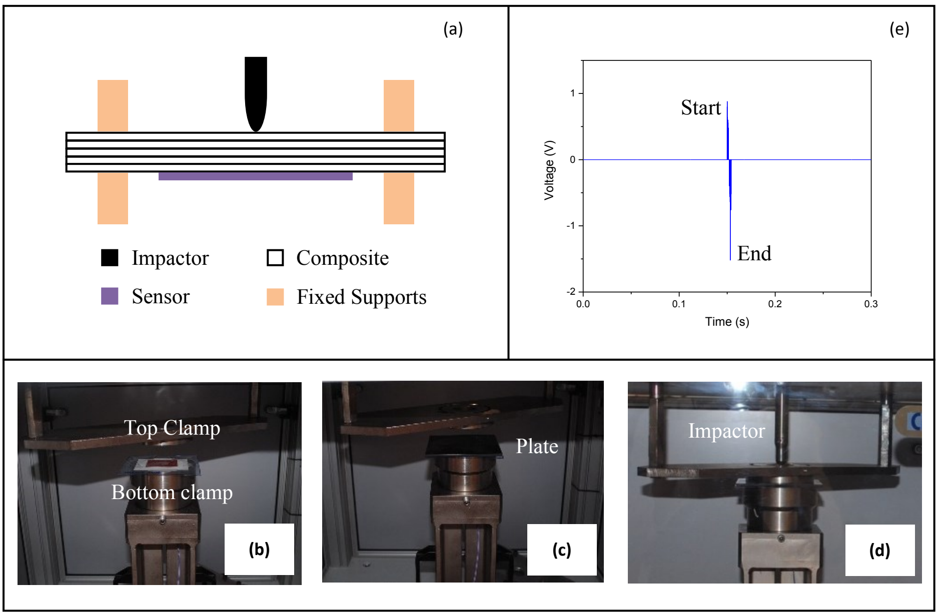


Fig. 4. Methodology used to investigate the applications of the sensor for impact velocity monitoring: (a) Schematic description of the experimental setup (transversal view). Description of the experimental procedure: (b) The triboelectric sensor is adhered to the bottom clamp of the impact machine. (c) A composite plate is adhered to the sensor. (d) The composite plate is clamped around the four edges and a controlled impact is applied. (e) The sensor electric responses are measured.

Fig. 4 shows a description of the experimental procedure which can be divided into four steps. First, the triboelectric sensor is adhered to the bottom clamp of the impact machine as shown in Fig. 2b. Secondly, a carbon plate with length of 120 mm, width of 120 mm and a thickness of 70 mm is adhered to the triboelectric sensor (Fig. 2c). Thirdly, the composite plate is clamped around the four edges and a controlled velocity impact is applied to the centre of the plate using the impactor of the drop-weight machine (Fig. 2d). The sensors adhered to the composite plates are strongly fixed to the impact machine using the clamping fixture of the impact machine (see fig. 2 (d)). Finally, the sensor electric response is obtained as shown in Fig. 4e. The figure 4(e) shows the history of the voltage changes during the impact. From the figure, it can be observed that the voltage goes through a positive and a negative peak which are associated to the start and the end of the impact respectively. Thus, the time interval between both peaks (3.1 ms) can be defined as the duration of the impact.

4.2 Prediction of the damage using the triboelectric sensor

The aim of this experiment is to verify that the developed triboelectric sensor can be used to predict the health state of the composite plates. For this purpose, composite plates are subjected to six controlled velocity impacts with the aim to measure the sensor electric responses by using the experiment indicated in Section 4.1. In addition, the area damaged as a result of the six different impacts is measured by using a C-Scan inspection system.

The main idea is to predict the damage state of the composite specimens using the correlation between the sensor voltage outputs and the area delaminated of the composite specimens, which can be named the Voltage-Damage relationship. Based on this bidimensional mathematical relationship, we propose a new methodology to predict the damage state of the composites.

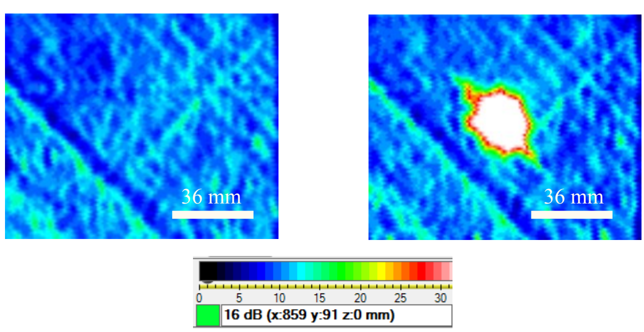


Fig. 5. C-Scan of the same composite plate before and after the impact.

The C-Scan inspection system is used to evaluate the health state of the composite plates for a controlled velocity impact. A comparison of a C-Scan image for the same composite plates before and after an impact is shown in Fig. 5. The legend scale on the left refers to the level of damage in the composite specimen, where the greenish blue colour (less than 20 dB) represents the undamaged area of the composite and the red colour (more than 25 dB) represents the severely damaged area of the composite. The yellow colour in between is associated to acoustic waves from 20 to 25 dB and corresponds to damage states where the composite specimens are partially damaged. From the image, it can be clearly observed the delaminated area which is attributed to the mechanical impact. The area damaged by the impacts is measured by the commercial software Image J 1.45s.

It is worthy to note that the composite plates used in this experimental have lower mechanical properties with respect to the specimens used in the experiment shown in section 4.1. This is done with the aim to clearly appreciate the area damaged by the different mechanical impacts in the C-Scan images.

5 Results and discussion

This section presents the results obtained from the experiments detailed in Section 4. Initially, the feasibility of the sensor for the detection and measurement impacts is analysed. Lastly, the section demonstrates the potential applications of the sensor for the prediction of the damage caused by controlled velocity impacts in composite structures.

5.1 Application of the sensor for impact monitoring

As mentioned in Section 4.1, composite plates were subjected to controlled impact velocities using a drop weight machine and the voltage and current responses of the triboelectric sensor were measured using a commercial oscilloscope and a digital multimeter, respectively. The idea is to investigate if the sensor electrical outputs are influenced by the velocity of the impacts.

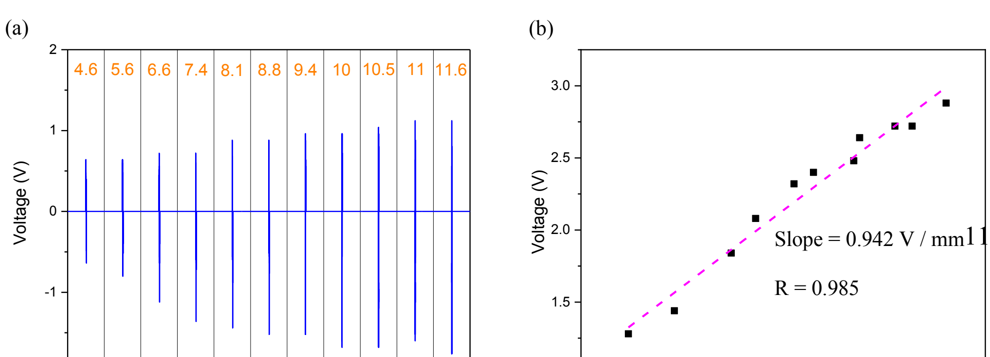


Fig. 6. Effect of the impact velocity on the electric outputs of the triboelectric sensor: (a) Voltage responses for various impact velocities in the range between 4.6 and 11.6 km/h. (b) Voltage amplitudes as a function of the sensor deformation.

Fig. 6 (a) displays the voltage outputs of the triboelectric sensor when the composite plates are impacted at various impact velocities ranging from 4.6 to 11.6 Km/h. It is noticed that higher impact velocities increase the voltage sensor outputs, which reach up to 2.88 V under the impact velocity of 11.6 km/h. As indicated in refs. [32, 33], the voltage output of a triboelectric sensor can be calculated as:

$$V = \frac{\sigma d}{\varepsilon_0} \qquad (1)$$

Where σ is the density of triboelectric charges, d is the distance between the frictional layers and ε_0 is the vacuum permittivity. In our triboelectric sensor, the distance between the frictional layers is constant because there is no separator between the layers. Therefore, the voltage changes are only due to the changes of triboelectric charges (σ) caused by the strong friction between the layers of the sensor.

Fig. 6 (b) shows that the voltage amplitudes of the sensor as a function of the impact velocity. From the figure, it can be observed that the voltage responses are influenced by the impact velocities and the amplitude of the voltage outputs increases from 1.28 to 2.88 V as the impact velocity increases from 4.6 to 11.6 km/h. Additionally, the results show a strong linear relationship between the sensor deformation and the voltage outputs with a Pearson coefficient of 0.985. Furthermore, the velocity-voltage relationship exhibits a very high sensitivity of 0.942 V/mm in the measurement range between 4.6 and 11.6 km/h. This is important as sensors with high sensitivity and linearity are always preferred for practical reasons and applications of the sensor.

To the best of our knowledge, only one study so far has investigated the potential of triboelectric sensors to measure impact velocities. As detailed in ref. [34], a triboelectric sensor composed of a mixture of polyvinylidene fluoride and polyvinyl pyrrolidone is used to detect the impacts applied by a free-falling ball at velocities of 1.4, 2.6, 3.6 and 4.4 m/s. The results revealed that the voltage sensor responses increase under higher velocities. A major limitation of the above study is the small energy of the impacts (less than 0.225 J), which is far from the energy of impacts in real case scenarios as per example bird strikes or hailstone impacts. In this study, the energy of the impacts is much higher and varies between 2 and 12 J as the impact velocity increases from 4.6 to 11.6 km/h (Supplementary Figure S2).

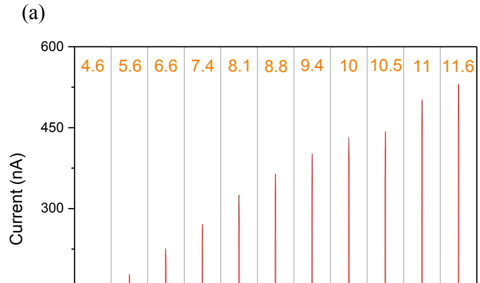
On the basis of the above results, it can be concluded that the voltage output depends on the velocity of the impacts and it increase linearly with the velocity for the measured range between 4.6 and 11.6 km/h. Furthermore, the relationship between the impact velocities and the voltage outputs show a high sensitivity for this measurement range. This demonstrates that the developed triboelectric sensor can be potentially used for impact velocity measurement.

Fig. 7a shows the current responses of the triboelectric sensor when the composite specimens are subjected to various impact velocities in the range from 4.6 to 11.6 Km/h. The graphic shows that the current electric outputs are affected by the velocity of the impacts and the current sensor responses increases from 111 to 530 nA as the impact velocity changes between 4.6 and 11.6 km/h. The current responses of a triboelectric sensor can be expressed as [35, 36]:

$$I = C\frac{\partial V}{\partial t} + V\frac{\partial C}{\partial t} \qquad (2)$$

Where C represents the capacitance of the sensor and V is the potential drop across the electrodes. As a result, the changes of current can be explained by the changes in the potential across the top and bottom electrodes.

(a)



(b)

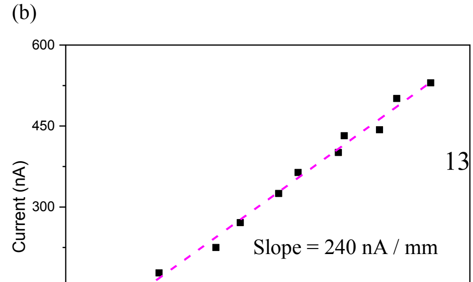


Fig. 6. Effect of the impact velocity on the triboelectric sensor electric responses: (a) Current outputs for various impact velocities in the range between 4.6 and 11.6 km/h. (b) Current amplitudes as a function of the sensor deformation.

Fig. 7b displays the current amplitudes of the sensor as a function of the impact velocity. From the figure 6(b), it can be clearly seen that the current outputs are strongly affected by the impact velocity and the amplitude of the current electric outputs increase with the impact velocity, as the velocity changes from 4.6 to 11.6 km/h. The experimental data points can be interpolated with a straight line which possess a strong linear behaviour (R = 0.996). Moreover, the current sensor responses are characterized by a very high sensitivity of 240 nA / mm in the measurement range investigated (between 4.6 and 11.6 km/h). This is of utmost importance from a technical point of view, because sensors with high sensitivity and linearity are preferred from practical considerations.

In general, it can be said that the current sensor responses are affected by the velocity of the impacts and the current responses increase linearly with the impact velocity applied to the composite plates. Furthermore, the relationship between the impact velocities and the current outputs show a high sensitivity for the detection range between 4.6 and 11.6 km/h. These results are important and can be said to expand the applications of triboelectric sensors for detection and quantification of impact velocities in composite structures.

5.2 Application of the sensor for health assessment

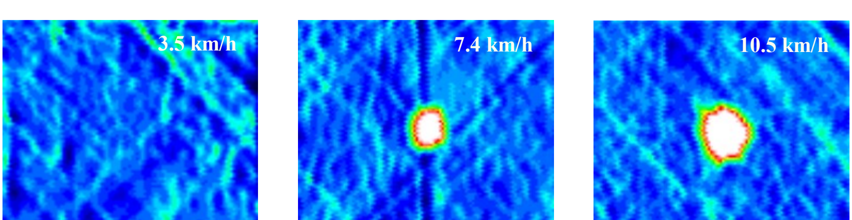


Fig. 8. C-Scan of the composite plates impacted at six different velocity impacts.

As explained in Section 4.2, six composite plates were subjected to various velocity impacts by using a drop weight impact machine and the impact area damaged is measured by using a C-Scan inspection system. Fig. 8 summarizes the c-scan results for the composite specimens impacted at six different impacts in the velocity range between 3 and 17 km/h. From the c-scan images, it can be clearly seen that as impact velocity increases, the area damaged as consequence of the impacts also increases.

Fig. 9 shows the relationship between the area damaged of the composite plates and the impact velocity. The plots show that the area damaged of the composite plates depends on the impact velocity and increase exponentially with the increase of the impact velocities. From the figure, it can be observed that there is a strong exponential relationship between the impact velocities and the area damaged with a Pearson coefficient of R= 0.999. Additionally, it also important to note that the relationship between the impact velocity and the area damage damaged of the composites plates is strongly affected by the nature of the materials. Therefore, this mathematical relationship is only representative of the carbon composite plates used in this experiment.

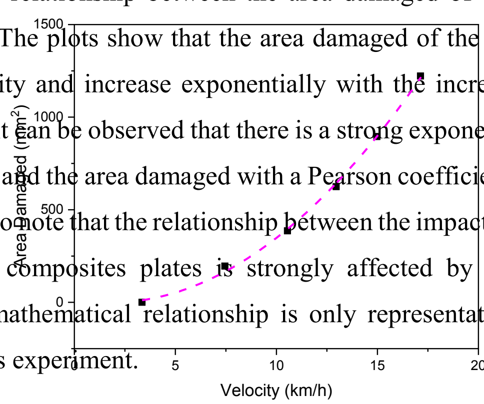


Fig. 9. Effect of the impact velocity on the area damaged of the composite plates.

Additionally, the developed triboelectric sensor is adhered to the composite plates and the sensor voltage outputs due to the impacts are measured by a commercial oscilloscope. The main goal of the experiment is to investigate the relationship between the sensor voltage outputs and the velocity of the impacts. Fig. 10 displays the sensor voltage outputs as functions of the impact velocity. From the figure, it can be observed an exponential relationship between the impact velocities and the sensor voltage outputs with a Pearson coefficient of R= 0.964 for the considered velocity range between 3 and 17 km/h.

Fig. 10. Effect of the impact velocity on the sensor voltage outputs.

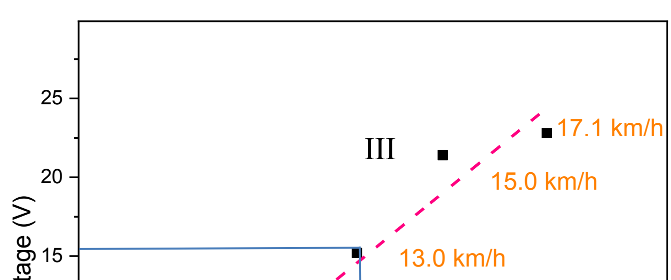


Fig. 10. Applications of the triboelectric sensor for prediction of the damage: Correlation between the area damaged of the composites and the sensor voltage outputs for the six different impacts.

It can be observed that the mathematical relationship between the area damaged and the voltage outputs exhibits three distinct regions. When the voltage outputs are below 4.4 V, the composite specimens are impacted at velocities below 3.5 km/h, which does not cause any damage on the composite laminates. In the region between 4.4 V and 15.2 V, the impact velocities vary between 3.5 and 13 km/h, which results in small delamination's below 625 mm2. In the region beyond 15.2 V, the composite plates are impact at velocities above 13 km/h which induces important damages in the composite laminates with delamination's which are bigger than 625 mm2. On the basis of these results, it can be concluded that the damage state of the composite plates (healthy or damaged) and the delamination size produced by the impacts can be predicted by the developed triboelectric sensor. This is important as it demonstrates that triboelectric sensors can be successfully used to estimate the health state of the composite structures used in airplanes, wind turbines and other civil structures.

Table 1: The table indicates the sensitivity, linearity and response time of the sensor.

Characteristic	*Units*	*Triboelectric*
Sensitivity	V/mm^2	0.0165
Linearity	Dimensionless	0.981
Response time	ms	0.1

Table 1 summarizes the sensitivity, the linearity of the input-output relationships and the response time of the suggested triboelectric sensor. The results demonstrate that the relation between the voltage outputs and the delamination size shows a constant sensitivity, which is beneficial for the practical applications of the sensor. Moreover, a strong linear relationship of the damage-velocity relations with a high Pearson coefficient can be observed for the developed triboelectric sensor in the entire measurement range between 0 and 1200 mm^2.. Additionally, it is also important to mention that the developed triboelectric sensor possesses a faster response time, which is critical for the real time detection of impacts in composite structures. These sensor characteristics can be used to demonstrate the outstanding performance of the developed triboelectric sensor for impact monitoring and health assessment in composite structures, such as aircrafts or wind turbines.

In summary, this section proves that the electric responses of the developed triboelectric sensor are strongly affected by the impact velocities and the damage state of the composite plates. This is important as it demonstrates that the tribolectric sensors can be also used for the prediction of the damage state of composite plates (healthy or damaged) and estimation of the size of the delamination caused by impacts. This can be used for important applications as health assessment of the composite structures used in aircrafts, wind turbines or bridges.

6 Conclusions

The prediction of the damage caused by impacts is of vital importance for monitoring the health state of composite structures such as aircrafts or wind turbines. The main achievement of this work is to demonstrate for the first time that triboelectric sensors can be potentially used for the purposes of health assessment in composite structures. This is very important as impacts can harm the integrity of the composite structures through delamination and other fault mechanisms, which are difficult to detect by visual assessment.

Initially, the fabrication of the triboelectric sensor based on polyvinyl fluoride nanofibers and a thin film of polypropylene is presented. The sensor is self-powered and does not require an external power supply, so this is an energy saving and environmentally friendly sensor. The fabrication process of the sensor is very simple and does not require expensive materials or equipment's, which brings down the manufacturing cost of the sensor. Additionally, the fabrication process can be easily developed for large-scale production, which offers a promising alternative for producing such sensors on an industrial scale using a low-cost technology.

Furthermore, the paper demonstrates the applications of the suggested sensor as self-powered impact sensor. The results show that the voltage and the current outputs increase proportionally with the impact velocities and a good linear relationship between the impact velocity and the sensor electric outputs (voltage and current) is found. Furthermore, it can be observed a very high impact sensitivity in a wide velocity range between 4.6 and 11.6 km/h.

Eventually, the paper also investigates the potential of the developed sensor for structural integration assessment in composite structures. In this respect, it can be observed that the sensor electric responses are proportional to the extension of the damage in the composite specimens, which verifies that the electric responses of the sensor can be used to predict the damage state of the composite plates (healthy or damaged) and the size of the delamination caused by impacts. This is important as it extends the applications of triboelectric sensors for the purposes of health assessment in composite structures used in airplanes, wind turbines and other civil structures.

In our view, this paper presents a solid progress toward the practical applications and implementation of triboelectric sensors as self-powered velocity sensors. Furthermore, the paper presents a new approach for the prediction of the delamination caused by impacts using the velocity-voltage-damage relationship. The findings of this study demonstrate that triboelectric sensors can be potentially used for dual purposes of impact monitoring and delamination assessment in composite structures, which can have important applications for the monitorization of the impacts and the prediction of the impact damage in aircrafts, bridges and other composite structures.

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